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RF FRONT END RECEIVER FOR GPS/GALILEO L1/E1

Filipe Palhinha[a], Ricardo Pereira[a], Duarte Carona[a,*], António Serrador[a], Mário Véstias[a], João Silva[b], Tiago Peres[b], Pedro Silva[b]

[a]*ADEETC/ISEL/IPL, Lisboa, Portugal*
[b]*DEIMOS Engenharia, Lisboa, Portugal*

Abstract

The upcoming Galileo system opens a wide range of new opportunities in the Global Navigation Satellite System (GNSS) market. However, the characteristics of the future signals require the development of new GNSS receivers. This paper presents the developed GNSS receiver architecture (including the Radio Frequency (RF) Front-End and the baseband Hardware (HW) platform), and describes the development of the experimental Global Positioning System (GPS)/Galileo L1/E1 RF Front-End (based on Maxim's MAX2769 chip), capable of being integrated in a space mission, done in the scope of the REAGE project. The results obtained with this new device are presented, focusing on the impact of the Intermediate Frequency (IF) bandwidth on the GNSS signal tracking enabling improvements of more than 50% quality.

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Keywords: GPS L1; Galileo E1; RF Front End; GNSS

1. Introduction

The Galileo system (Europe's global navigation system, currently being deployed [1]) and GPS modernization will soon provide new signals (with increasingly complex modulations and multiplexing schemes) which will enable performance enhancements in terms of availability, accuracy, and interference robustness of GNSS measurements and positioning solutions.

Galileo's E1 signal, with its Binary Offset Carrier (BOC) modulation, while not competing with Galileo's E5 signal (one of the most advanced and promising signals of the Galileo system), still provides a huge improvement in terms of precision and multipath robustness when compared with the current GPS L1 C/A and L2 C signals, while keeping the required receiver complexity at a considerably low level.

Galileo's Initial Operational Capability (IOC) is expected by 2014 (18 satellites, with which early services to Europe can begin) and Final Operational Capability (FOC) by 2020 (30 satellites, including 3 spares). Furthermore, as a result of the ongoing GPS modernization, Europe's and USA's efforts towards Galileo-GPS interoperability, the

* Corresponding author. Tel.: +351-218317000 ; fax: +351-218317114.
E-mail address: dcarona@deetc.isel.ipl.pt

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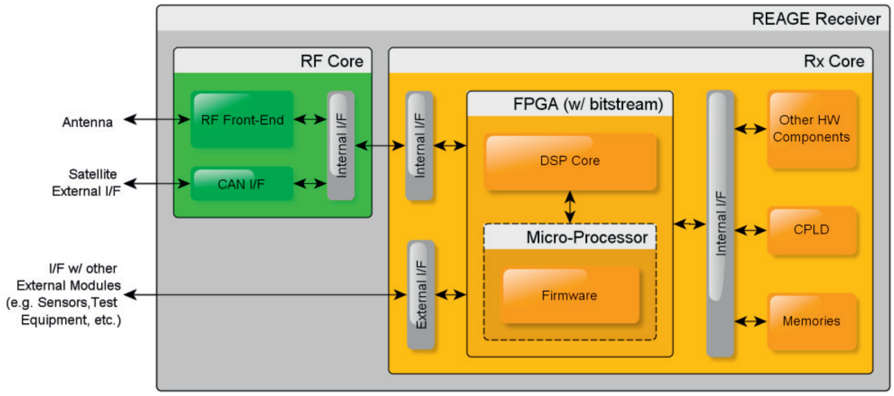

Fig. 1. REAGE receiver architecture

future Galileo E1 and GPS L1 C signals will be compatible, enabling receiver simplification and increased availability at a low cost.

In the scope of the REAGE project (funded by ADI, under the Portuguese QREN initiative, contract no. 21553), DEIMOS and ISEL have developed a low-cost experimental multi-system (Galileo and GPS) GNSS receiver for the L1/E1 band, targeted for use as a non-critical redundant sensor for space missions, but which can also be used for terrestrial (ground or airborne) applications, such as Unmanned Aerial Vehicle (UAV) navigation.

The REAGE project included the design and implementation of both RF front-end and baseband HW platform of a GPS/Galileo L1/E1 receiver, keeping it as flexible as possible to allow trade-off analysis of receiver parameters and performances. This paper provides an overview of the REAGE receiver's architecture (including the Radio Frequency (RF) Front-End and the baseband Hardware (HW) platform) and describes the development of the experimental Global Positioning System (GPS)/Galileo L1/E1 RF Front-End, implemented using available commercial grade components (based on Maxim's MAX2769 chip) and capable of being integrated in a space mission.

The precision of a GNSS receiver's measurements depends, not only on the signal characteristics and DSP algorithms performance, but also on RF front-end characteristics, as overall noise figure, filter(s) bandwidth(s), ADC sampling frequency and local oscillator stability. This paper also addresses some test results and an analysis of the RF front-end's frequency response and of the impact of its bandwidth on code phase measurements' quality.

This paper is organized as follows. Section 2 presents an overview of the GNSS receiver developed in the scope of the REAGE project. Section 3 describes the prototype of the RF core. Section 4 presents the results obtained with the RF Core Prototype and finally section 5 concludes the paper.

2. Architecture of the REAGE Receiver

The REAGE project's primary goal was to build a space receiver for Low Earth Orbit (LEO) missions using available commercial or, in the farthest extent, industrial grade components. The selection criteria of components and materials that composes each block of the architecture was based on an expected LEO mission duration of 7 to 10 years, which determines for instance the critical temperature constraints to guarantee operability, and also the fact that the receiver may accept gradual ionization energy deposit that eventually will lead to inoperability of the receiver at predicted End Of Life (EOL) stages. Space HW related issues, as redundancy and remote re-configuration, were taken into account in the definition of the REAGE receiver architecture, illustrated in Figure 1.

The REAGE receiver is composed by two main modules, namely the RF Core and the Rx Core. The RF Core includes the HW in charge of signal reception, conditioning, down-conversion, and sampling. The Rx Core includes a HW part and a SW part. The HW part is in charge of the high-frequency Digital Signal Processing (DSP) of the Intermediate Frequency (IF) and Baseband (BB) signals and is implemented on a Field-Programmable Gate-Array

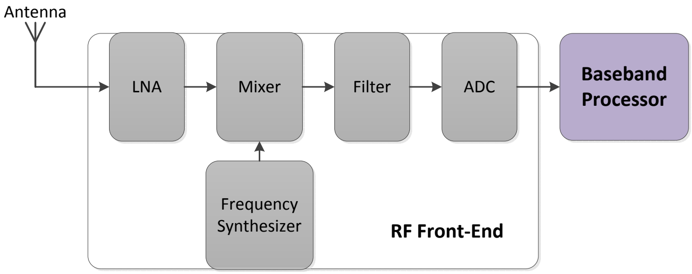

Fig. 2. RF front-end architecture (main blocks).

(FPGA). The software (SW) part controls the HW part of the Rx Core, generates measurements, and computes the navigation solution (and performs the overall control of the receiver)

The Rx Core includes a DSP HW accelerator (the DSP Core), a micro-processor, memory modules, a Complex Programmable Logic Device (CPLD)-based system controller, different internal and external interfaces (for communication between the different receiver modules and between the receiver and the satellite and other external modules, as additional sensors) as well as other HW components.

The RF Core includes the receiver front-end and a Controller Area Network (CAN) interface (for communication with the systems on-board the satellite).

A generic GNSS receiver architecture is shown in Figure 2, where the RF front-end components and their interface with the antenna and baseband processor, are highlighted.

The RF front-end consists of a Low-Noise Amplifier (LNA); a (quadrature) Mixer, in charge of the down-conversion of the RF signal to baseband or low IF; a Frequency Synthesizer, to generate the correct clock frequency to the Mixer; a Filter (to select the signal band); and an Analog-to-Digital Converter (ADC), to digitize the received signal which is fed to the Baseband Processor, in charge of the GNSS signal acquisition and tracking (as well as measurement generation and navigation solution computation).

A low-noise amplifier (LNA) must be located very close to the detection device to reduce losses in the reception chain. A good LNA has low noise figure, F, (around 1dB) and a large enough gain (e.g. 20dB) [2]. For best noise performance (low total noise figure), the first amplifier stage should have the lowest noise figure in a chain as shown in equation 1.

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots Gn - 1} \quad (1)$$

It is important to take this into account when choosing the LNA used in the first stage, since GPS L1 and Galileo E1 signals have a very low power (for Galileo E1, the typical received power on ground is around -127dBm [3]).

A quadrature Mixer is needed to down-convert the received signal (with an RF carrier frequency of 1.57542 GHz) to baseband or low-IF I and Q signals. To achieve this, a low-side Local Oscillator (LO) is required. Since the performance of the mixer depends on the characteristics of the LO, the later should remain stable in frequency.

A Frequency Synthesizer (usually referred to as Local Oscillator, LO) is required to feed the Mixer with the correct frequency for the down-conversion of the RF signal to baseband (or low IF). This is usually accomplished with a (local or external) frequency standard (as a crystal oscillator), a Phase-Locked Loop (PLL) a Voltage Controlled Oscillator (VCO), and a Frequency Divider, allowing the output frequency to be precisely tuned to a multiple (not necessarily integer, depending on the frequency divider) of the reference frequency.

A programmable Band-Pass Filter (BPF) or Low-Pass Filter (LPF) is used to extract the desired frequency band (the one including the signal of interest) from the Mixer output while rejecting the remaining frequencies (thus filtering out noise and other unwanted signals). Typically the bandwidth for GPS L1 C/A can be as low as 2 MHz while for GPS L1 C and Galileo E1 signals it may range from 4 to 16 MHz. The required bandwidth is therefore defined by the Galileo E1 signal.

After the I/Q demodulator and baseband filter/amplifier, the signal is converted to digital domain. To perform the conversion to digital domain a quantization process is needed, which adds (quantization) noise to the desired signal, leading to a SNR reduction.

The baseband processor (Rx Core in Figure 1) is responsible for processing the signals coming from the RF Front-end. It includes:

- An FPGA, in which the receiver's processor (which runs the receiver firmware) and a DSP HW accelerator core are implemented;
- Memory modules, including Read Access Memory (RAM) used by the micro-processor, and Programmable Read Only Memories (PROMs) used to store the FPGA's bitstream, the receiver's firmware and non-volatile data;
- A CPLD-based system controller (in charge of receiver reconfiguration and communication with the satellite via the CAN interface);
- Different internal and external interfaces, for communication between the different receiver modules and between the receiver and the satellite and other external modules. Available interfaces include the RF Core interface, ethernet, Universal Asynchronous Receiver/Transmitter (UART), an FPGA Mezzanine Card (FMC) connector, Peripheral Component Interconnect Express (PCIe) connector, and General Purposes Input/Output (GPIO) pins, among others;
- Other HW components (as voltage regulators and level-converters, among others).

The REAGE baseband processor (Rx Core) was used not only to support the performance analysis of the REAGE Front-End (RF Core) but also to demonstrate its potential and applicability. It supports GPS and Galileo signals and features programmable digital input filters, 20 independent HW channels (one "master" channel can be used to control other "slave" channels) - with code and carrier NCOs, mixers, primary and secondary code generators and five complex correlators each, for a total of 100 complex correlators - and an embedded microprocessor (in charge of overall receiver control, acquisition, tracking loop closure, measurement generation, and navigation solution computation), as well as redundancy for some critical components and the ability of self-programming (in case the FPGA's bitstream becomes corrupted - due to radiation or any other reason - or if remote reconfiguration and/or updates are required).

3. RF Core Prototype

After the identification and description of the correct architecture for the proposed scheme, a procurement process took place to find a solution in the market that complied with the requirements. A System on Chip (SoC) from Maxim IC [4] that implements the described functionalities was selected: the MAX2769. This chip has a complete receiver chain, including a dual-input LNA (for active and passive antennas), Mixer, Baseband/IF Filter, Programmable Gain Amplifier (PGA), VCO, fractional-N Frequency Synthesizer, Crystal Oscillator, and a multi-bit ADC (up to 4 bits). The total cascaded noise figure of this receiver is as low as 1.4dB.

Figure 3 shows the developed prototype, based on the MAX2769, which includes two antenna inputs (one for active antennas and the other for passive antennas) as well as a digital interface to use with external processing units (used to program the front-end as well as to send the digitized data to the base-band processor. Figure 4 shows the block diagram of the prototype.

An external RF SAW band-pass filter with a bandwidth of 80MHz and an attenuation of 25dB in the reject band is used between the LNA and Mixer (to pre-filter the input signal and reduce out-of-band interference). Filtering a bandwidth of 80 MHz at 1575.42 MHz is very selective. This can only be accomplished with this integrated filter. It acts as a pre-filter and then the filter inside the transceiver will do the right bandwidth selection in IF. This kind of filter is commonly used in this type of applications because of its superior line phase characteristics and rejection qualities.

The power supply circuitry was designed according with components specifications. It is powered by 3.3V external supply to produce 2,85V with a consumption of approximately 30mA in full mode operation (this power consumption does not include any consumption associated with the CAN bus).

Fig. 3. REAGE RF Core prototype (CAN interface on the left and RF front-end on the right).

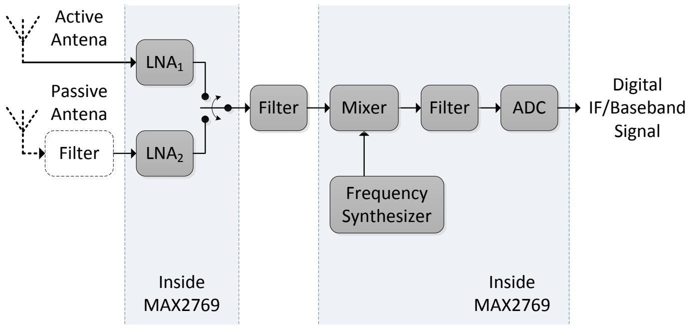

Fig. 4. Developed RF front-end prototype block diagram.

4. Test Results

For the purpose of performance comparison, three different configurations were defined: a low bandwidth configuration (2.5 MHz, the default configuration for the Max2769 RF Front-end), a higher bandwidth configuration (8 MHz), and an intermediate bandwidth configuration (4.2 MHz). An IF frequency of 4 MHz and a sampling frequency of 16.368 MHz (default values for the MAX2769) were used for all tests.

The results obtained with the different configurations were compared in terms of the RF front-end's frequency response and of the noise in the code measurements generated by the REAGE receiver. The test results and discussion are presented in the next sub-sections. At the time of writing, only GPS L1 results were available. Nevertheless, expected results for the case of Galileo E1 signals are also discussed. Additionally, due to the availability issues, the Rx Core was implemented (using the REAGE bitstream and firmware) on a Xilinx ML605 development board, whose characteristics and functionalities are similar to those of the Rx Core (in what concerns the scope of the tests).

4.1. Frequency Response

The estimated frequency response of the RF front-end for the different configurations is shown in Figure 5. These results were obtained using MATLAB scripts to compute the power spectral density of the RF front-end outputs, assuming white Gaussian noise at its input (which, for the case of GNSS, is an acceptable assumption since the signal power is well below the noise floor before correlation).

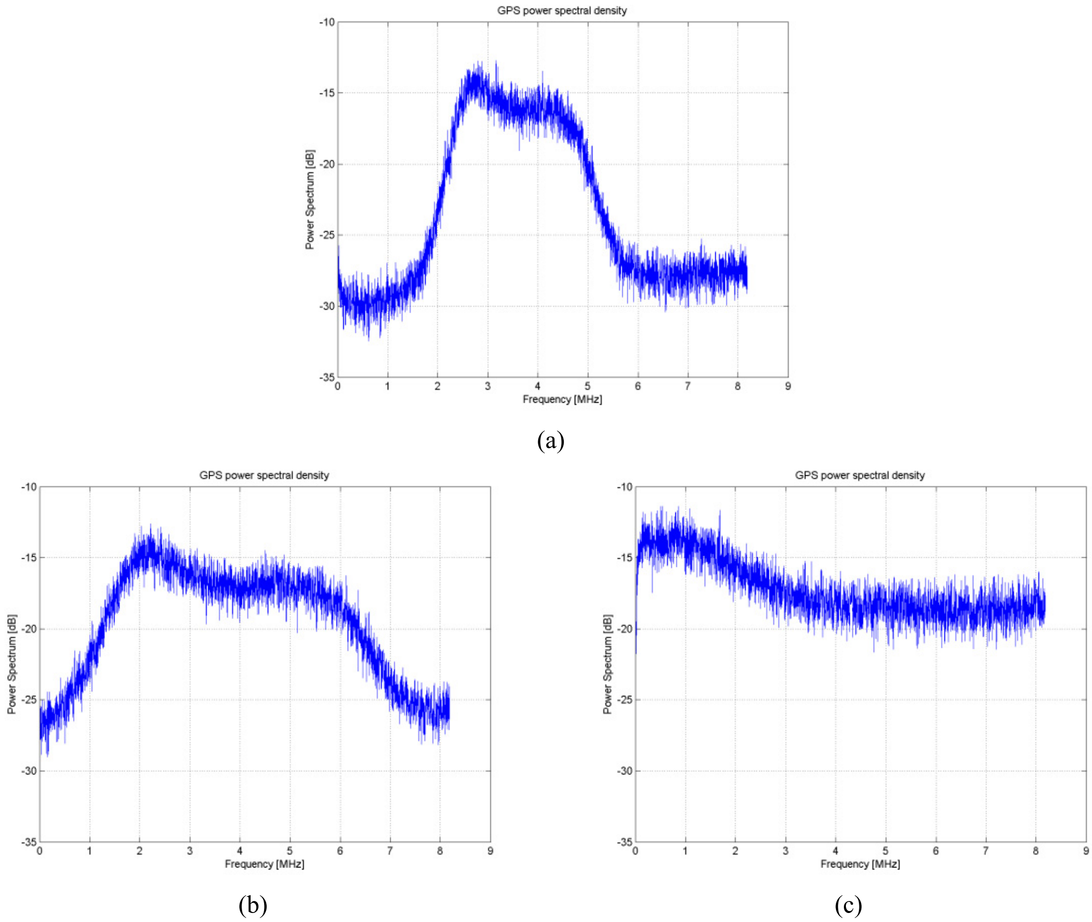

Fig. 5. RF front-end frequency response for bandwidths of (a) 2.5 MHz, (b) 4.2 MHz, and (c) 8 MHz (using IF configuration).

A slightly asymmetric pass-band gain is observable for all configurations. This effect seems to be more relevant for higher bandwidths: although, for a bandwidth of 2.5 MHz, the difference between the maximum and minimum gains within the pass-band is below 3 dB, for a bandwidth of 8 MHz this difference rises above 5 dB.

To be noted that the above plots are only good estimates of the RF front-end's frequency response if the input is actually white Gaussian Noise. If this is not the case, the effect discussed above may be related with the input noise characteristics and not with RF front-end limitations. Nevertheless, although this asymmetry may impact the shape of the auto-correlation function, for GPS L1 and Galileo E1 signals this is expected not to have a considerable impact.

4.2. Code Phase Measurements Error

The Rx Core was used to obtain code phase measurements using the different RF Core configurations. The correlator spacing was set to 1 sample (equivalent to 0.0625 chip for GPS L1 and Galileo E1 signals). Figure 6 shows the Auto-Correlation Functions (ACFs) for the different bandwidths and signals. It can be seen that decreasing the bandwidth, besides implicating a loss of correlation power (more evident for the Galileo E1 signal due to its higher bandwidth), causes a rounding of the ACF peak. This reduces the receiver's tracking loops sensitivity, translating into

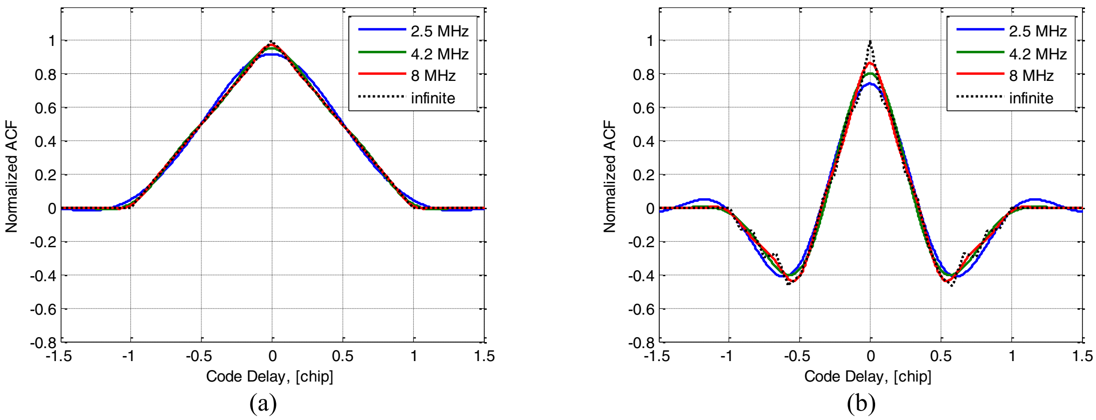

Fig. 6. Auto-correlation functions for different RF front-end bandwidths for (a) GPS L1 C/A and (b) Galileo E1 B signals.

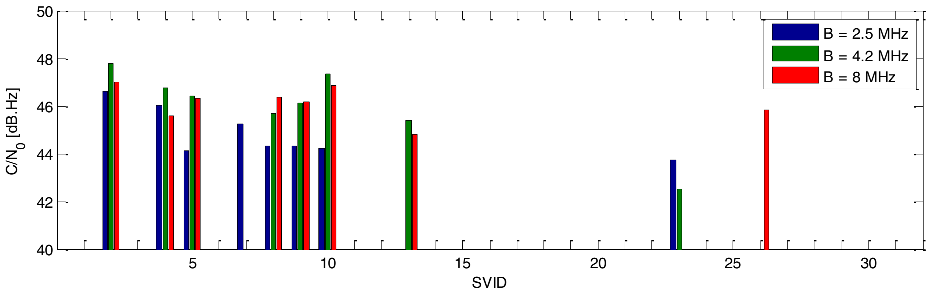

Fig. 7. Tracked satellites and estimated C/N_0 during tests.

higher measurement noise. Conversely, higher bandwidths, besides reducing correlation power losses due to filtering, enable a clearer discrimination of the ACF peak, decreasing measurement noise.

A total of 10 GPS satellites were tracked during the tests. Figure 7 shows the tracked satellites and their corresponding C/N_0 (estimated by the receiver). The tests for the different bandwidths were done sequentially and a maximum of 8 satellites were simultaneously tracked (which is why some satellites are visible for some tests and not for others). It can be noted that, in general, the estimated C/N_0 is slightly lower for the lower bandwidth configuration (indicating that some signal power might be lost due to filtering).

Figure 8 illustrates the distribution of the obtained code tracking errors for GPS L1 and for the different bandwidths (maximum, minimum, mean and quartiles, red circle is an identified outlier and was ignored). As expected, higher bandwidths are associated with lower code measurement noise (on average). It can be seen that the average code tracking noise drops from 3.3 m, for 2.5 MHz bandwidth, to 2.1 m, for 4.2 MHz, and 1.75 m, for 8 MHz.

It can also be seen in the Figure that the improvement from increasing the front-end bandwidth from 4.2 MHz to 8 MHz is less evident than when the bandwidth changes from 2.5 MHz to 4.2 MHz. This is also expected since the bandwidth of the GPS L1 C/A signal is around 2 MHz. This could also be expected from the analysis of Figure 6-a, which shows that the shape of the ACF is similar for both 4.2 MHz and 8 MHz of bandwidth. However, for the case of Galileo E1 signals, whose bandwidth is around 16 MHz (although about 90% of the power is concentrated in a bandwidth of 4 MHz), the improvement is expected to be more evident than for GPS L1 signals, which is also suggested by Figure 6-b.

Based on the results presented above and on the Galileo E1 signal characteristics (CBOC(6,1,1/11) modulation), it is expected that Galileo performances in terms of code measurements noise outperform the ones for GPS L1 by a

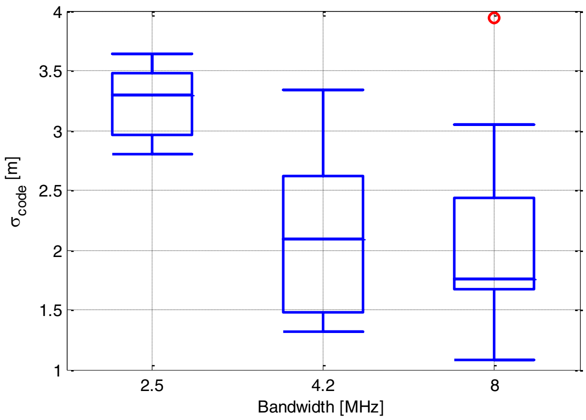

Fig. 8. Distribution of code tracking errors for different bandwidths (for GPS L1 C/A signals).

factor of, at least, 3, corresponding to measurement noise below 1 m, as confirmed in other studies as the ENCORE project [5].

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5. Conclusions

DEIMOS Engenharia and ISEL have developed a low-cost experimental multi-system (Galileo and GPS) GNSS receiver for the L1/E1 band, targeted for use as a non-critical redundant sensor for space missions (that can also be used for terrestrial applications), which relies on commercially available components. This paper provides an overview of the REAGE receiver architecture, detailing the RF Front-end.

An analysis focusing on the RF front-end characterization and configuration optimization has been performed. Experimental results for GPS signals were presented, demonstrating applicability of the RF front end and preliminary receiver performance figures (in terms of code measurements noise). Expected results for Galileo E1 signals were discussed based on the experimental GPS L1 results.

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